17102

k Technology Corporation

AECV 2007

Integrated Thermal Modules for Cooling Silicon and Silicon Carbide Power Modules

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Program Team

Acknowledgements

k Technology Corporation – Thermal Component Design

- Design – Parameter Evaluation
- Fabrication – Heat Spreaders/Fins
- Thermal/Fluid Bench Tests

Comprehensive Power – Converter/Motor System

- System analyses – Thermal Loads
- Converter Controls (Design Fab and Test)
- Motor Test and Evaluation

Semikron, New Hampshire – Major Supplier of Power Modules

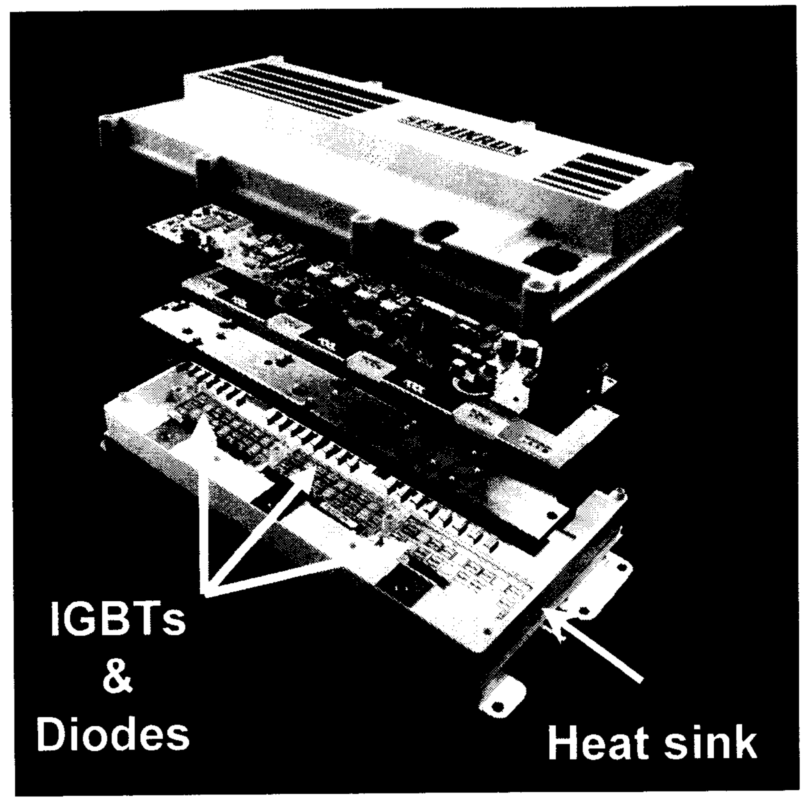
- Engineering Support
- Power Module Supplier
- Power Module Modification for SiC Diodes

U.S Army – TARDEC

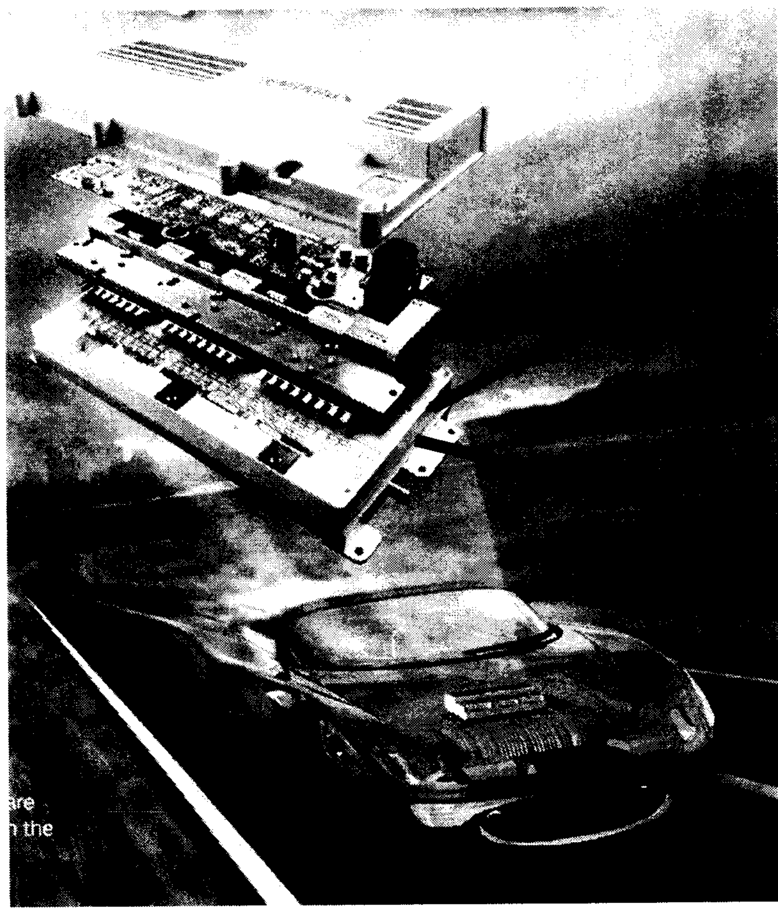
- Technical Support
- Program Management
- System Requirements

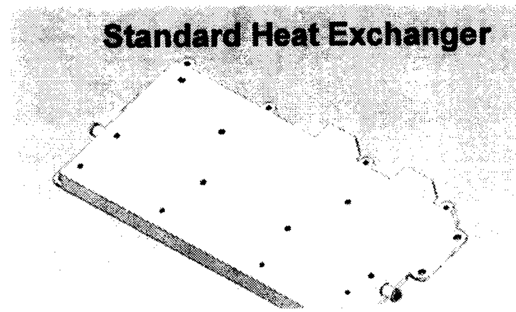
SKAI Inverter Module for Heatsink Evaluation

- SKAI Module contains complete drive inverter
  - DC to 3 phase AC
  - IGBTs & gate drive
  - Bus capacitors
  - Current sensors
  - Digital Signal Processor
- Heat sinks and semiconductors can be substituted for comparison

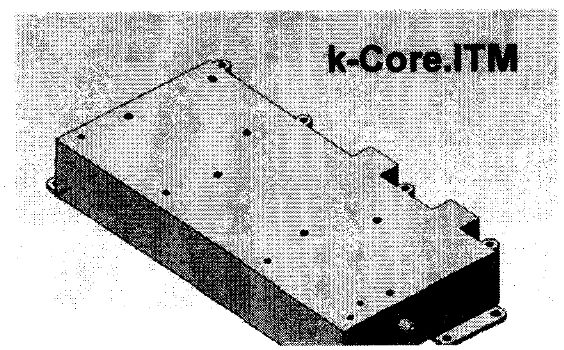


Integrated Thermal Module (ITM) Performance Gains for Semikron SKAI™





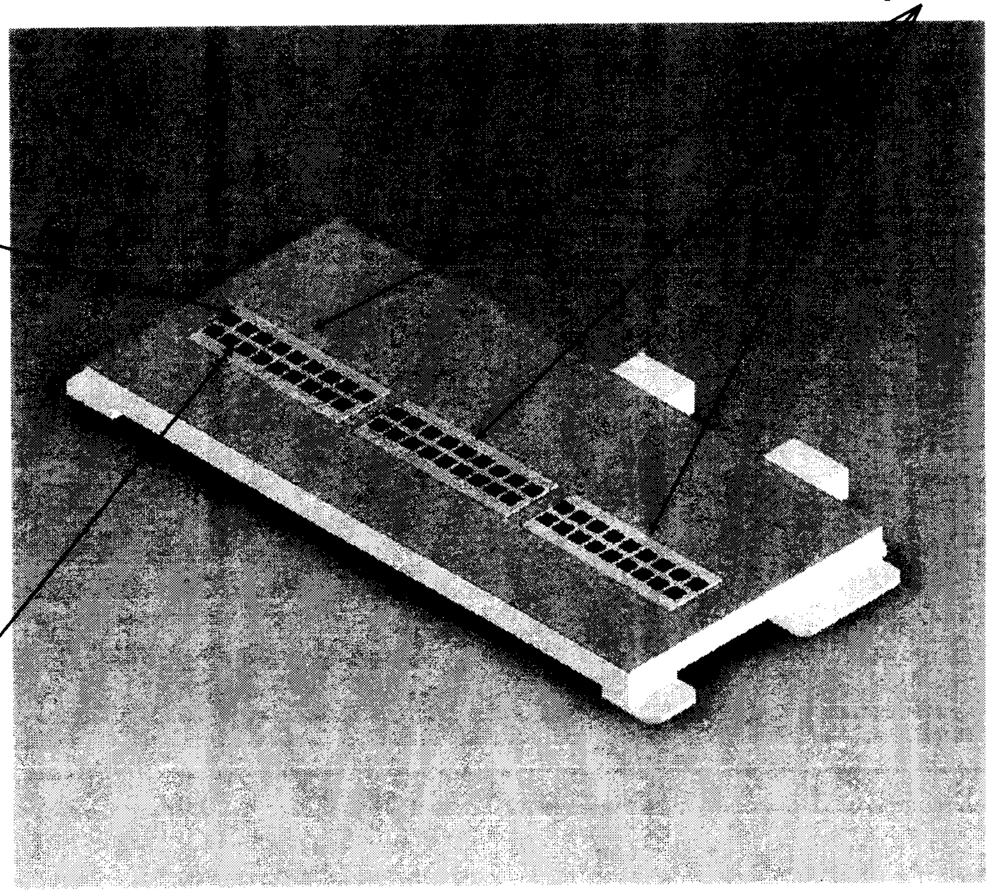
SKAI Power = 100 kW



SKAI Power = 160 kW

Loads

Heat Loads for SKAI 100kW
6 Operational Conditions



Vehicle Operational Conditions

Case

1. Normal Operation at High Speed
2. Normal Operation at Low Speed
3. Acceleration at High Speed
4. Acceleration at Low Speed
5. Stall at 0 degrees Offset
6. Stall at 30 degree Offset

IGBT, Diode Heat loads

Design Load Cases SKAI

Case 3
Acceleration at High Speed

SKAI 3001GD12
Acceleration at High Speed

Assumed Parameters:

Motor Voltage	400 VAC RMS line to line
DC Bus Voltage	620 VDC
Phase Current	225 Amperes, RMS line to line
Motor Frequency	240 Hz
PWM Frequency	10 kHz
Power Factor	0.96
Power	150 kW

Calculated Losses

	IGBT, per	IGBT total	Diode, per	Diode total	Total
A Upper	49.4	296.6	15.2	45.6	342.2
A Lower	49.4	296.6	15.2	45.6	342.2
B Upper	49.4	296.6	15.2	45.6	342.2
B Lower	49.4	296.6	15.2	45.6	342.2
C Upper	49.4	296.6	15.2	45.6	342.2
C Lower	49.4	296.6	15.2	45.6	342.2
Total					2053.2

Case 6
Stall 30 Degrees Offset

SKAI 3001GD12
Stall, 30 degree offset

Assumed Parameters:

Motor Voltage	7 VAC RMS line to line
DC Bus Voltage	620 VDC
Phase Current	150 Amperes, RMS line to line
Motor Frequency	0 Hz
PWM Frequency	2.5 kHz
Power Factor	0.96
Power	0 kW

Calculated Losses

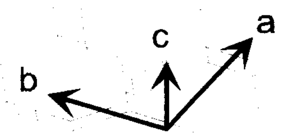
	IGBT, per die	IGBT total	Diode, per die	Diode total	Total
A Upper	13.2	79.3	0	0	79.3
A Lower	0	0	41.3	123.9	123.9
B Upper	0	0	0	0	0
B Lower	53.3	319.8	0	0	319.8
C Upper	13.2	79.3	0	0	79.3
C Lower	0	0	41.3	123.9	123.9
Total					726.2

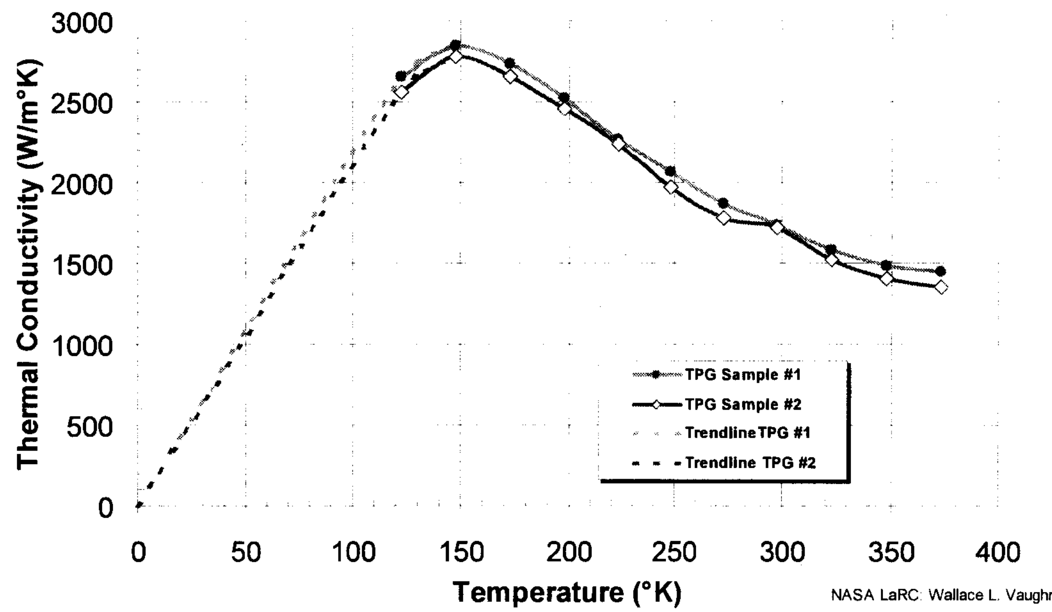
Heat Load: 2053W/3 (684 Watts) is over all three phases. Circuit board for each phase is 113mm x 40 mm

Material Systems

Advanced Pyrolytic Graphite (APG)

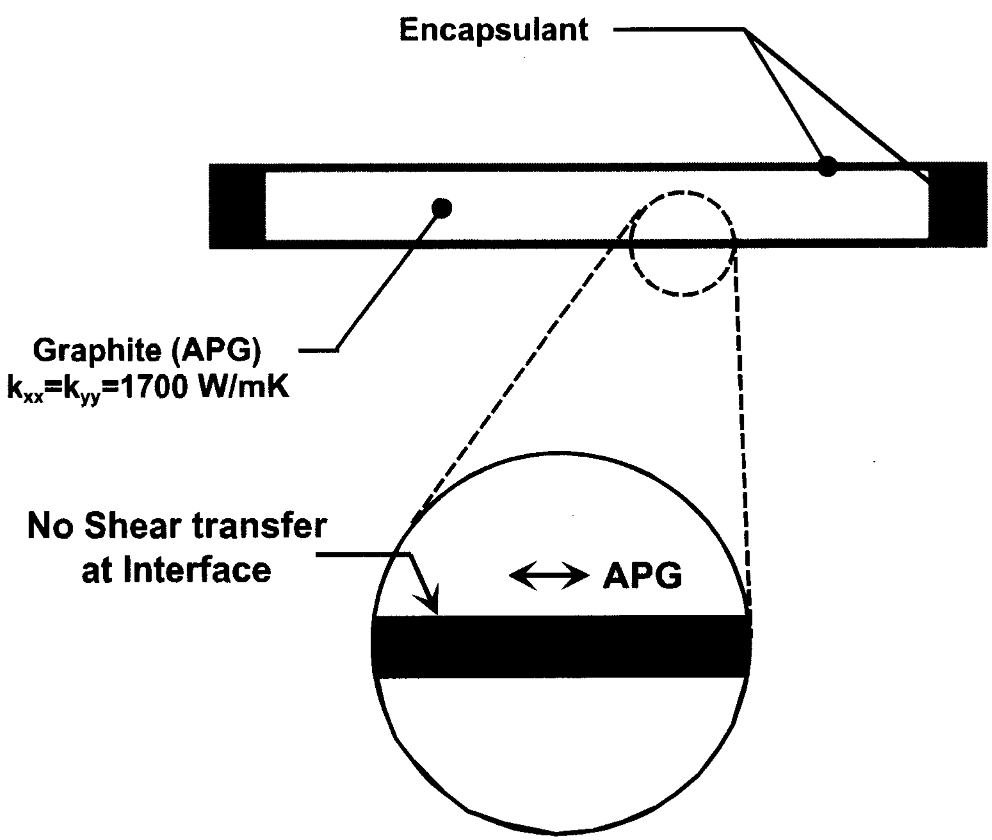
Advanced Pyrolytic Graphite (APG), Mosaic Spread 5 to 10 Deg



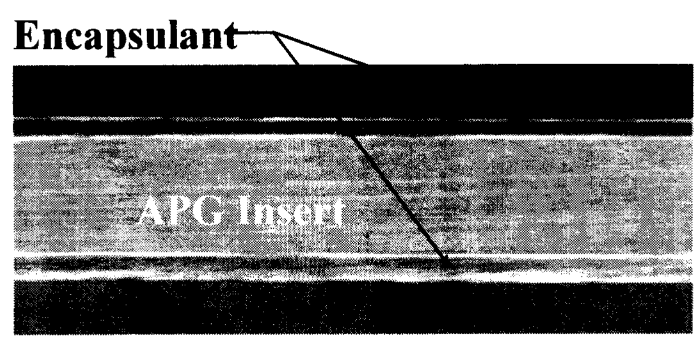


- k_{ab} = 1700. W/mK
- k_c = 10. W/mK
- E_{ab} = 120 Msi
- E_c = 5.0 Msi
- CTE_{ab} = -1.0 x10^{-6} $^oC^{-1}$
- CTE_c = 25. x10^{-6} $^oC^{-1}$
- Tensile Strength$_{ab}$ = - ksi
- Tensile Strength$_c$ < 0.2 ksi

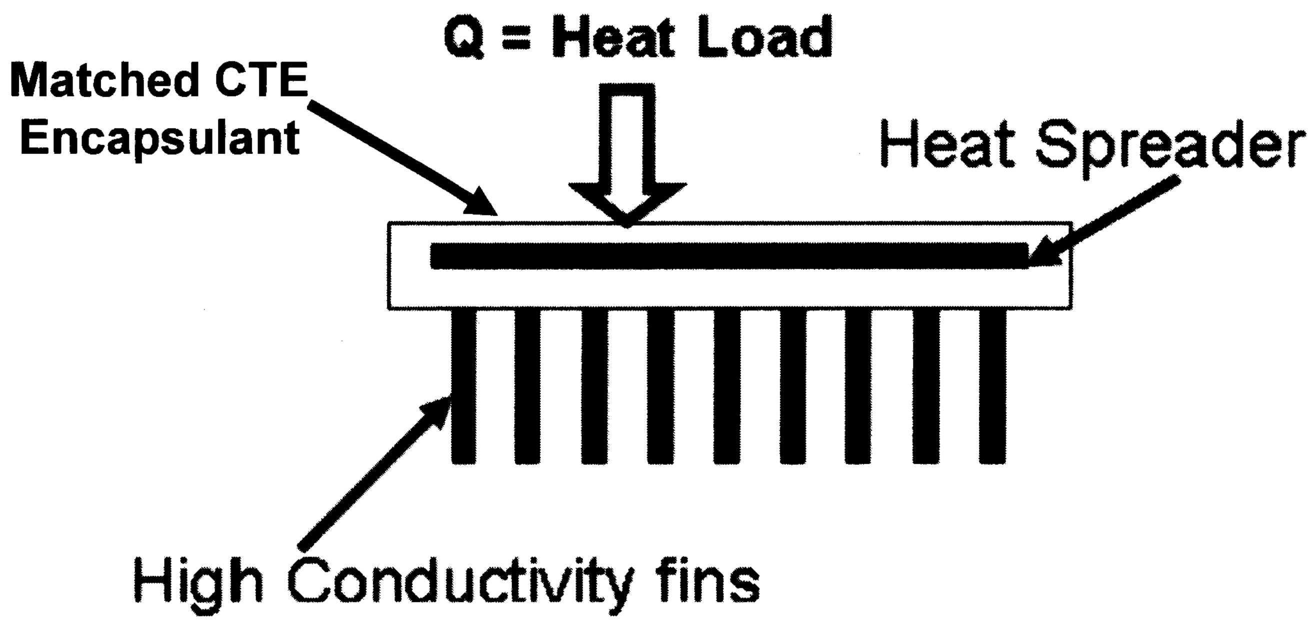
k-Core™ Material Concept



- Encapsulated APG material system
- Advanced pyrolytic graphite provides a high k path
- Encapsulant sets the CTE and structural properties
- Encapsulant material selected to satisfy requirements



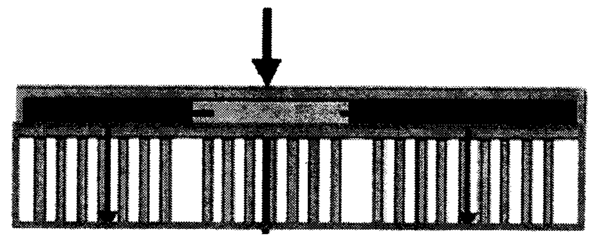
Use of APG in Integrated Thermal Module



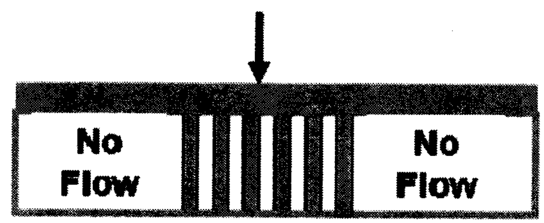
Integrated Thermal Module (ITM) Configurations

Configuration	Spreader	Pins/Fin/Foam
Wide Plenum	Alum	Alum Pins
Wide Plenum	k-Core.Al	Alum Fins
Wide Plenum	k-Core.Al	APG Fins
Wide Plenum	k-Core.mm	APG Fins
Channel	Alum	APG Fins
Channel	k-Core.Al	APG Fins
Channel	Alum	POCO Foam
Channel (Baseline)	Alum	Alum Pins

Wide Plenum
Heat Transfer to Side Channels

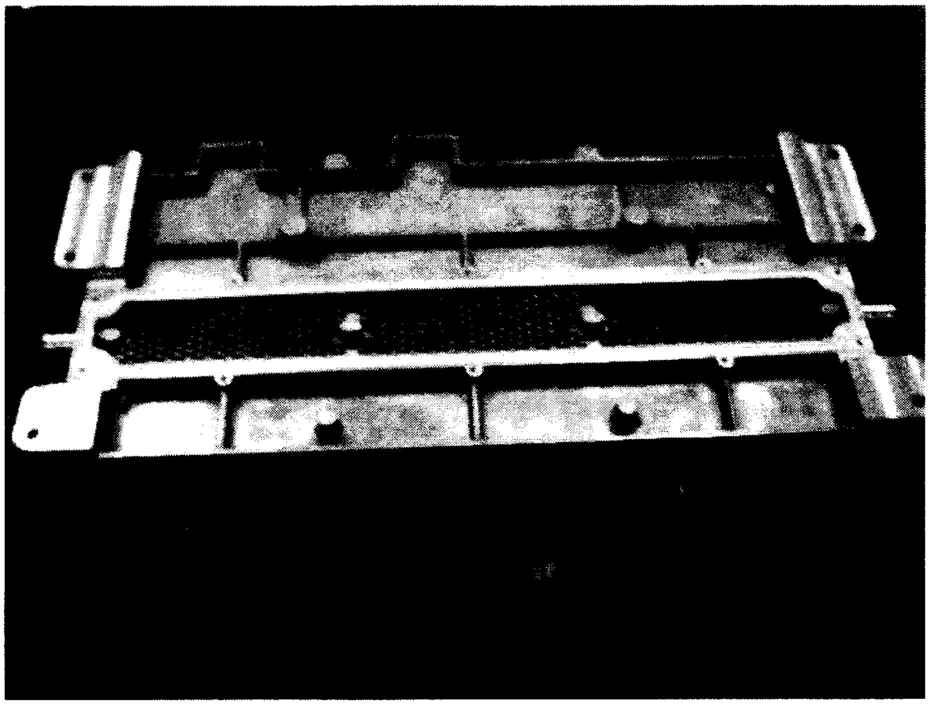


Basic
Heat Sink with Single flow Channel



Bench Tests

Off-the-Shelf Semikron Heat Sink Base Line



(inverted – Cover Removed)

- All Aluminum
- Pin Fins
- Fluid Flow 5 to 15 Liters/min
- Single Flow Channel

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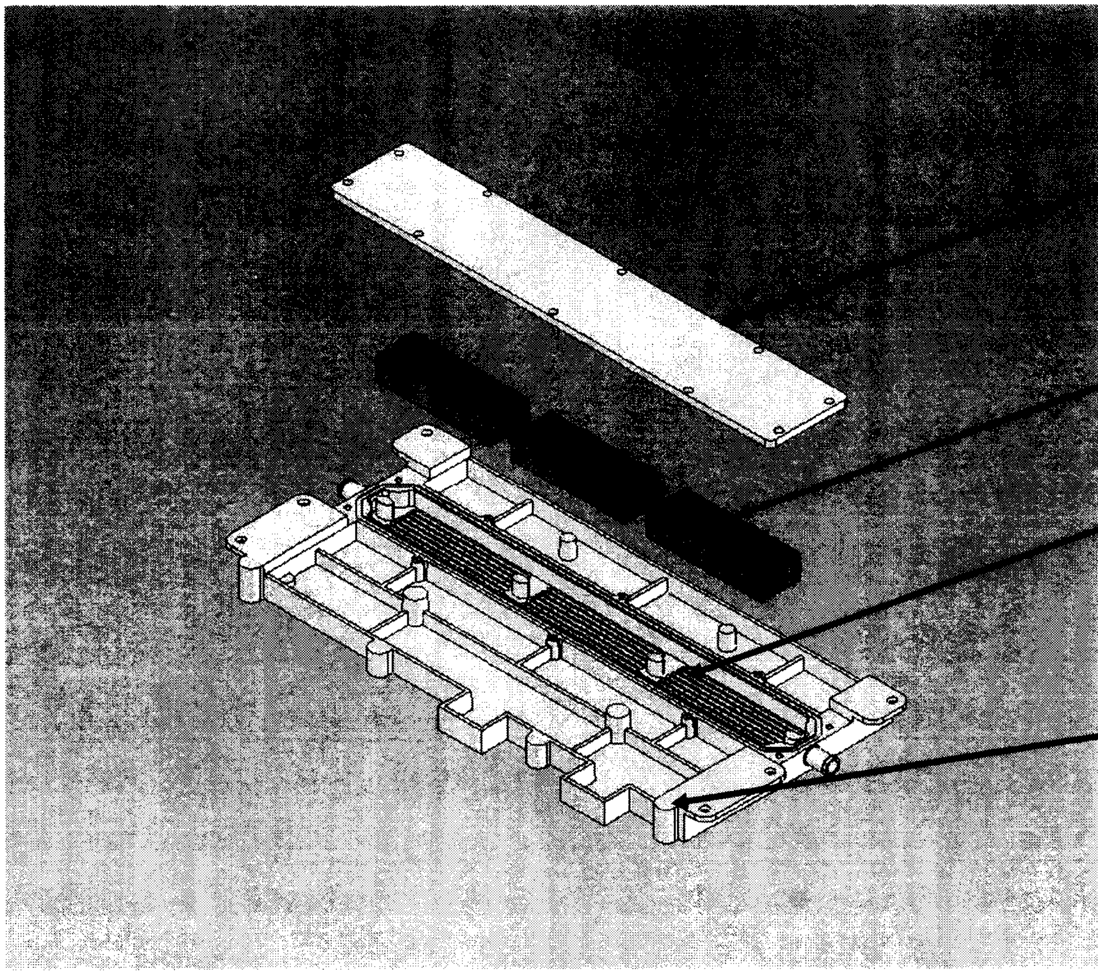
Fabrication with k-Core Fins



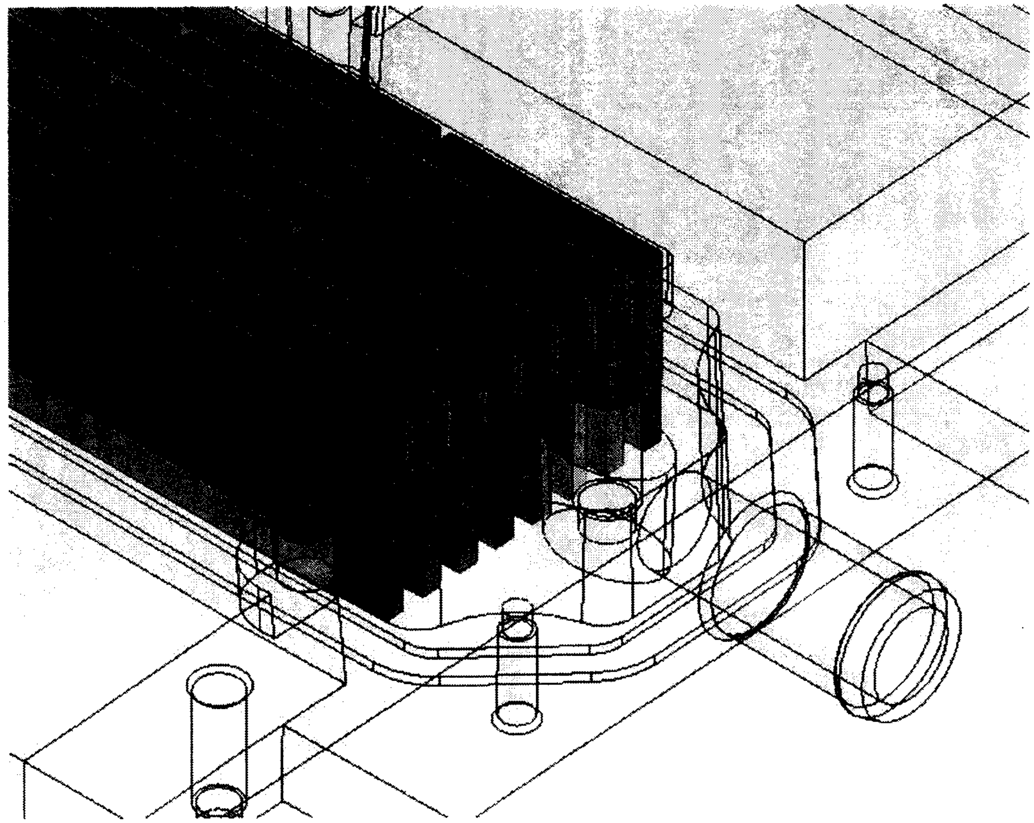
Cover Plate

k-Core Fins

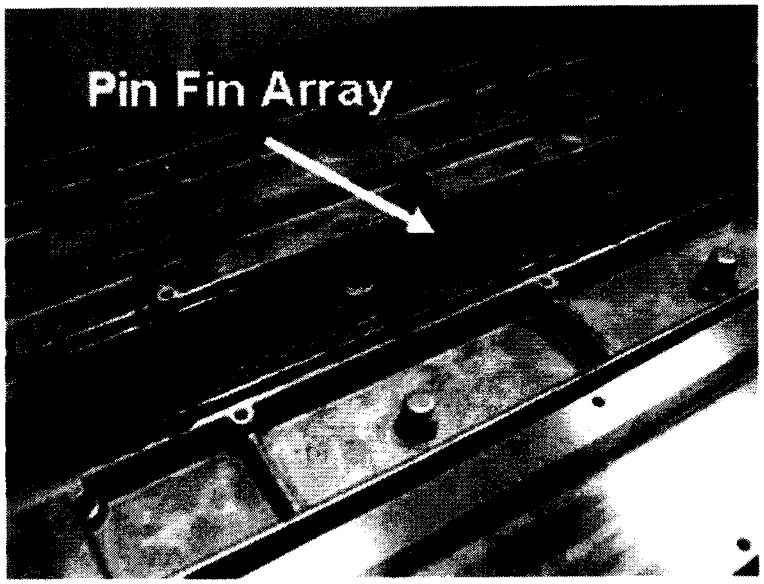
Machined Grooves in Place of Pin Fins

Modified Semikron SKAI Heat Sink

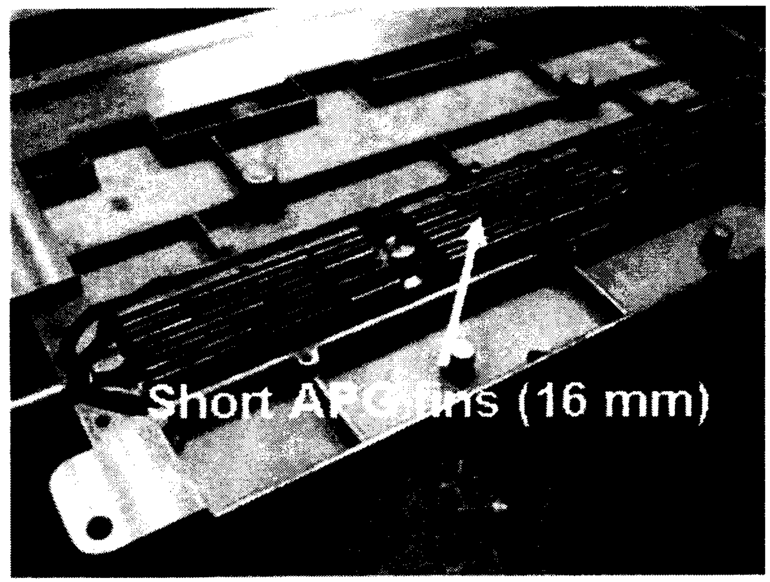
Assembly with k-Core Fins



Base Line and ITM with APG Fins

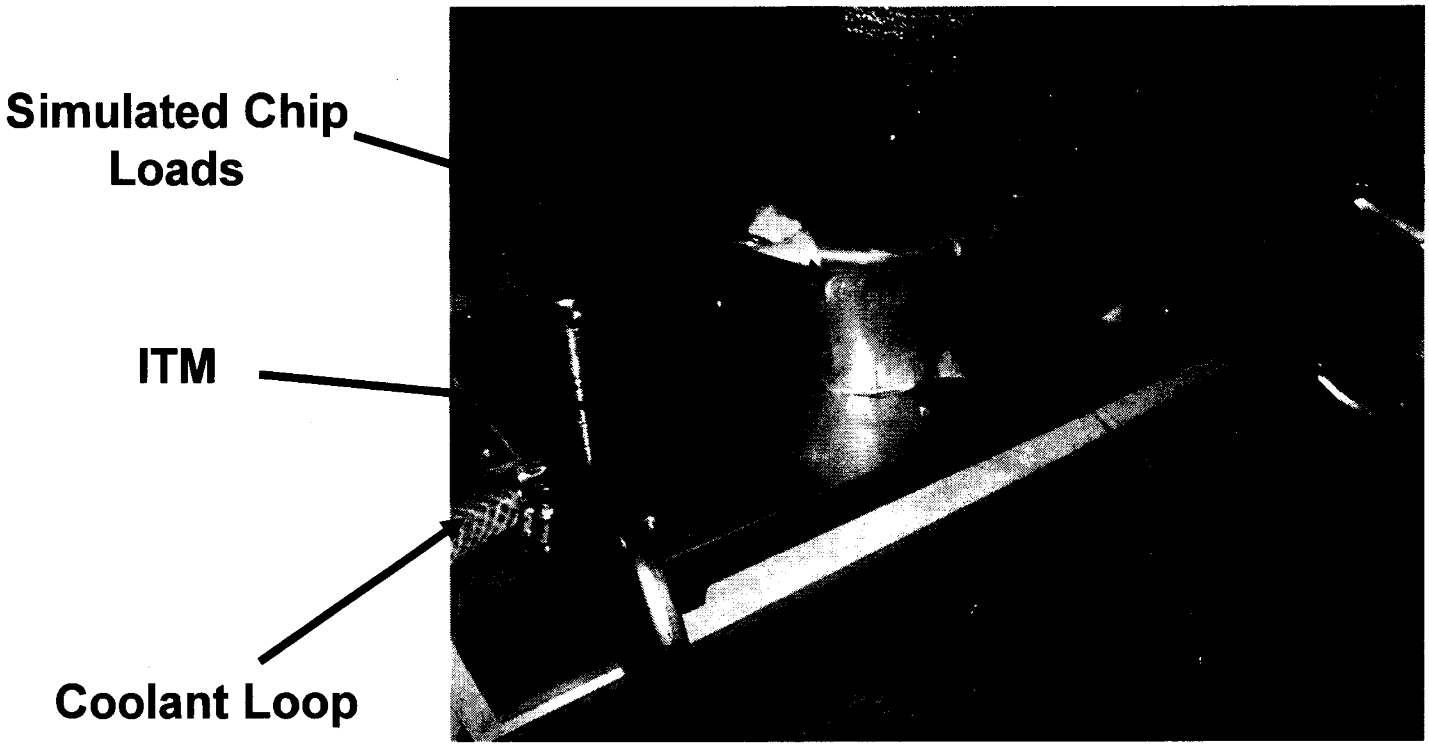


(a) Standard Heat Sink
with pin fin array

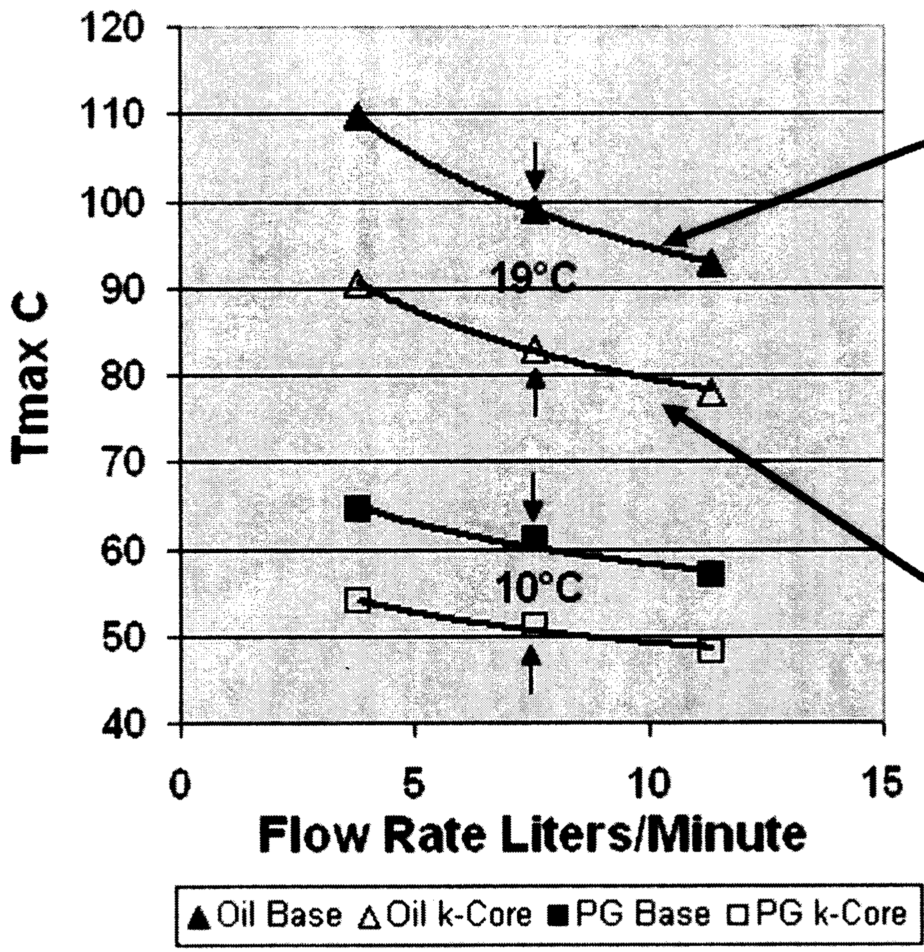


(b) ITM with APG Fins

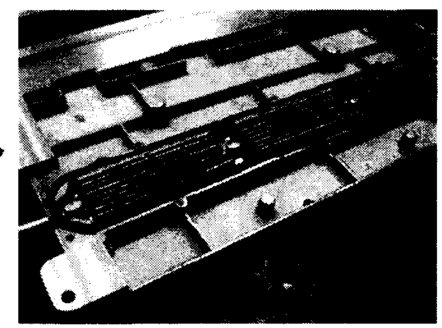
ITM In Bench Test



Reduction in $T_{surface}$ with ITM



Baseline Pin Array

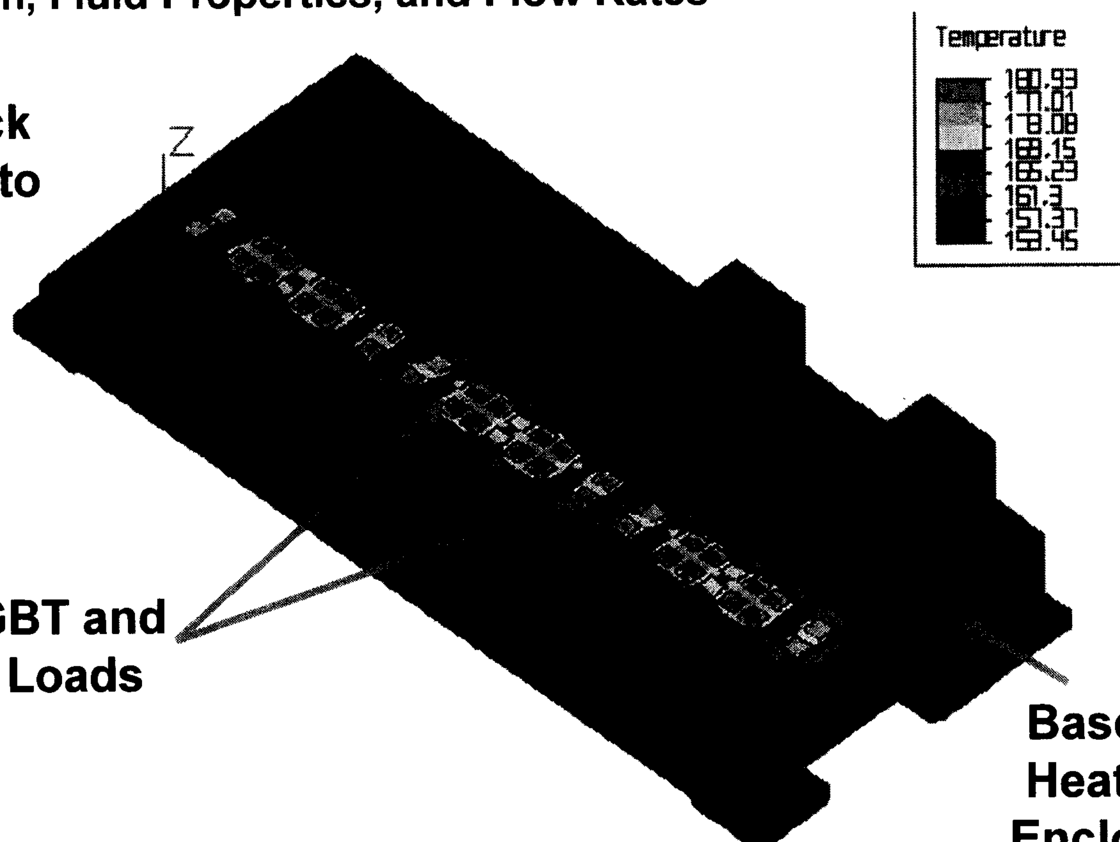


APG Fin ITM

Analyses

Typical 3d, Orthotropic Material Analysis

Convection Coefficients Based on Empirical Correlations with Fin Configuration, Fluid Properties, and Flow Rates

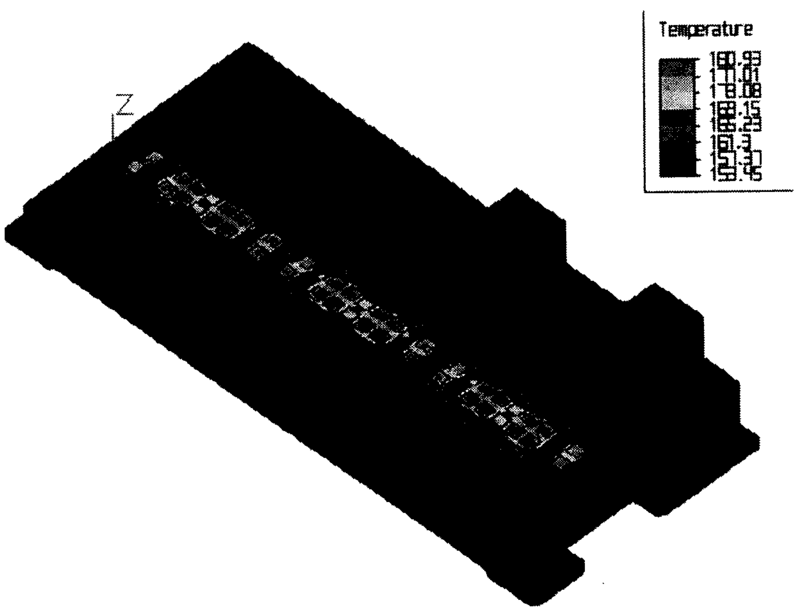


Includes Stack up from Chip to ITM Surface

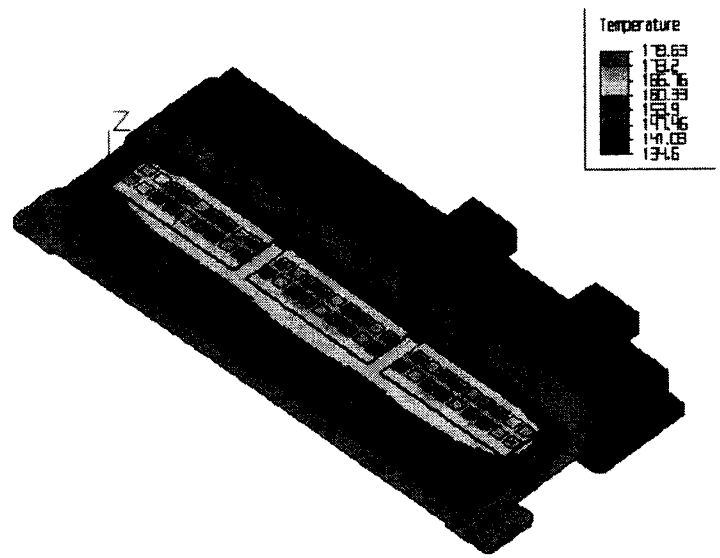
Individual IGBT and Diode Heat Loads

Baseline Heatsink Enclosure

Standard and Wide Plenum Analyses



Baseline Channel Cooling



Wide Plenum Cooling

Silicon Carbide

Silicon Carbide Electrical Characteristics

Electrical Characteristics

Symbol	Parameter	Typ.	Max.	Unit	Test Conditions	Note
V_F	Forward Voltage	1.65 2.6	2.0 3.0	V	I_F = 50 A T_J=25°C I_F = 50 A T_J=175°C	
I_R	Reverse Current	10 50	200 1000	µA	V_R = 1200 V T_J=25°C V_R = 1200 V T_J=175°C	
Q_C	Total Capacitive Charge	305		nC	V_R = 500 V, I_F = 50 A di/dt = 500 A/µs T_J = 25°C	
C	Total Capacitance	4500 396 325		pF	V_R = 0 V, T_J = 25°C, f = 1 MHz V_R = 200 V, T_J = 25°C, f = 1 MHz V_R = 400 V, T_J = 25°C, f = 1 MHz	

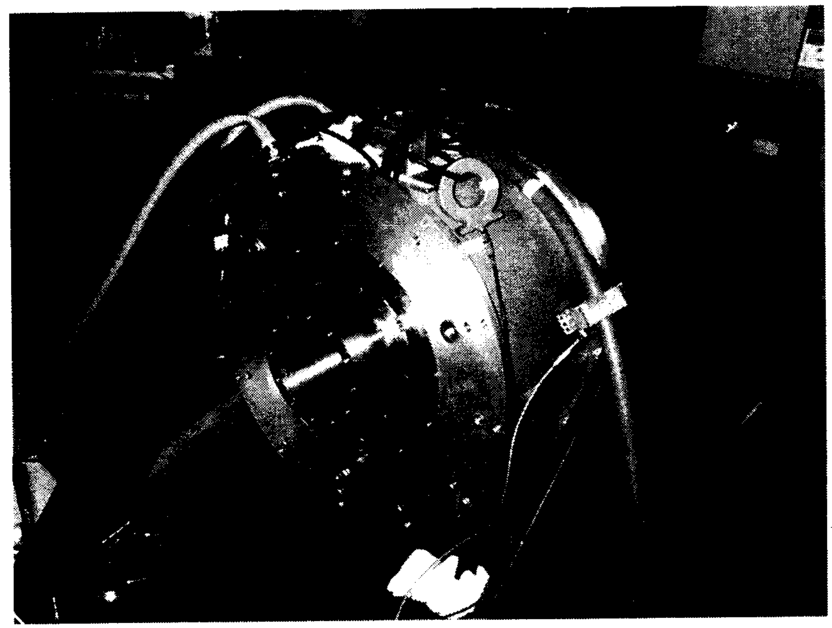
Note:

1. Assumes $\theta_{J\text{-}C}$ Thermal Resistance of 0.5°C/W or less.

Motor Tests

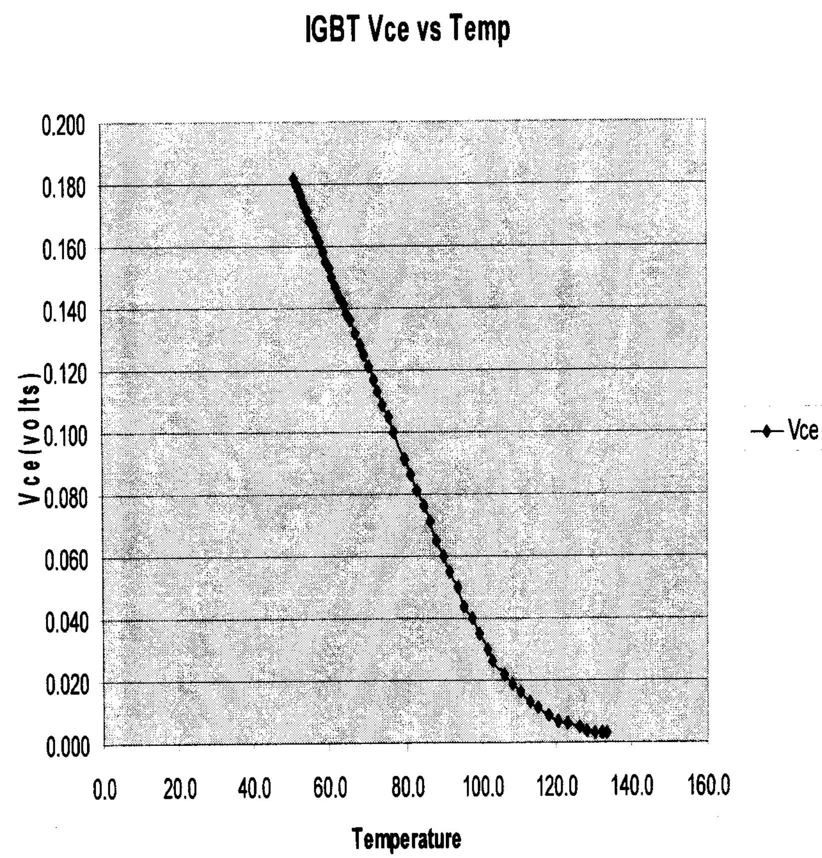
Motor Test Set Up

- Inverter load tests are performed with high horsepower PM motors on a back to back test stand
  - 650 VDC input to inverter
  - 0-480 Hz output to motor
  - 0-300 kW steady state
- Programmable load cycles with full four quadrant operation

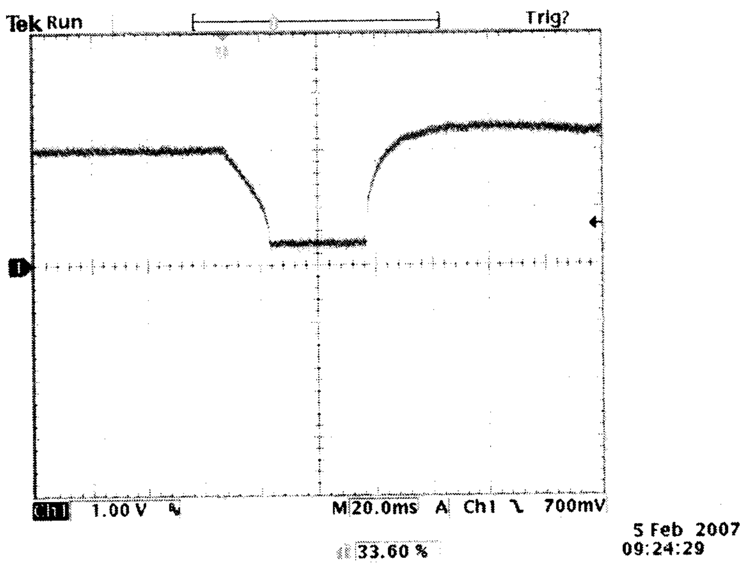


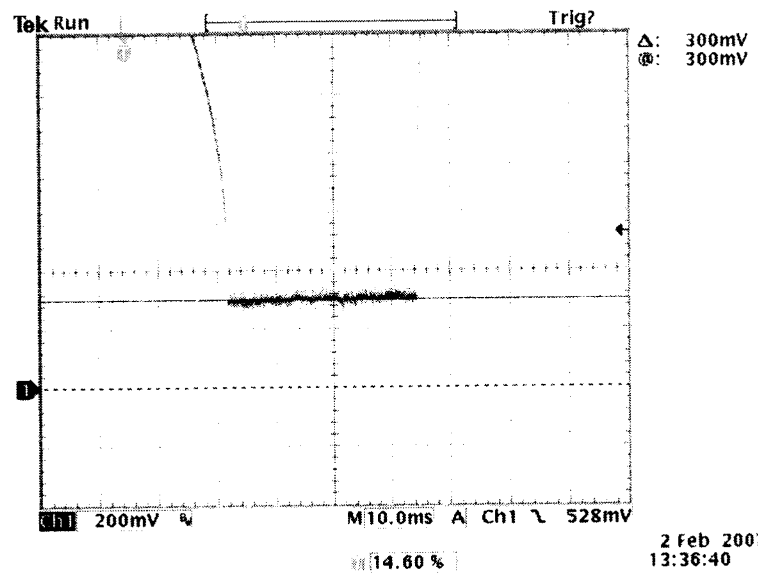
IGBT Die Temperature Measurement

- IGBT forward voltage is measured at a small reference current
  - Voltage decreases with increasing temperature
  - Offset will vary among wafers
- Scale can be calibrated by measurement at zero power
  - Data shown is for 500 amp IGBT
- Higher reference current is needed for resolution at higher temperature



Measurement of Thermal Resistance





- Heat the dice by feeding a known heat load into IGBTs
  - High current at low voltage
- Disable current and measure forward voltage at reference current
  - Voltage has known temperature dependency
  - Speed of measurement is vital

Motor Test Matrix

Motor tests X - Completed	Heat sinks					
	Baseline		ITM-1		ITM-2	
	Engine Oil	Propylene Glycol	Engine Oil	Propylene Glycol	Engine Oil	Propylene Glycol
SKAI-Standard		X				
SKAI-SiC Diodes		X				

SKAI-SiC Shows an 8% Reduction in IGBT Temp
versus SKAI Standard
Both Using Standard Heat Sink

Summary

Integrated Thermal Modules (ITMs) are being developed to cool power modules with high-temperature fluids.

3D FEM analyses, bench tests, and motor tests comprise the program.

The ITMs, in place of standard heatsinks, use a highly conductive pyrolytic graphite to passively cool power modules.

Initial results show that even simple ITMs can lower chip temperatures by 20°C and 10°C with engine oil and propylene glycol coolants, respectively.

Motor tests record real-time IGBT temperatures. Two converters, one using Silicon (Si) diodes and the other using Silicon Carbide (SiC) diodes, are being used for testing the ITMS.

Initial Motor tests with the baseline heatsink have shown that the SiC diodes lower IGBT temperatures by 8% as compared to Si diodes.